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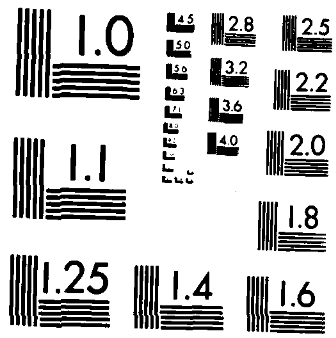

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NAVY EXPERIMENTAL DIVING UNIT
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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407

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ABSTRACT

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KEY WORDS:

Carbon Dioxide
Scrubber
Canister Duration
Recompression Chamber
Canister Flow
Environmental Control System

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This report is a revision of a paper first presented at the International Diving Symposium 1984, February 6-8, 1984, at New Orleans, LA.

INTRODUCTION

The standard two-lock aluminum recompression chamber is in common use in the U.S. Navy. It is designed for either permanent installation on ships and shore locations, or for portable use at diving sites. In most chambers, environmental control consists primarily of frequent or continuous ventilating from air banks or compressors. This method has the disadvantages of high air usage, high chamber noise levels during ventilation, poor temperature control, and increased operator effort. These disadvantages are particularly acute during longer treatment schedules or in hot climates. Commercially produced Environmental Control Systems (ECS) which provide heating and cooling and remove carbon dioxide are available. They have the potential not only of reducing air consumption and associated ventilation noise, but can also make chamber treatments more comfortable for patients, tenders and operators. The Navy Experimental Diving Unit (NEDU) has been evaluating an ECS system for use in a chamber for the past several years.

This report describes the series of unmanned tests used to determine the operating characteristics of the carbon dioxide scrubber component of the ECS which included airflow and canister duration.

METHODS

A two-lock aluminum recompression chamber was used which is 3.4m (11 ft) long and has a diameter of 1.5m (5 ft). The volume of the inner lock is 3,850 liters (136 cubic feet), and of the outer lock 1,840 liters (65 cubic feet). Instrumentation penetrators were installed in place of two viewports which allowed the addition of carbon dioxide (CO_2) and sampling of chamber atmosphere.

A Kinergetics, Incorporated (6029 Resada Blvd., Tarzana, CA 91356) ECS was installed. This system has two independent components, a carbon dioxide scrubber and a heater-chiller. The heater-chiller blower was not used in this study to control temperature but the blower was used to help mix chamber atmosphere during all studies. Temperature remained at approximately 75°F (24°C) for all tests. The CO_2 scrubber (Model DH-10, serial number 105.39-774) consists of a simple metal canister containing approximately 8 pounds (3.6 kg) of CO_2 absorbent through which chamber air is circulated by a 24 volt DC electric blower.

During all studies, canisters were packed with fresh HP Sodasorb (W.R. Grace and Company, Atlanta, GA 30336) and weighed to ensure uniformity. A container of water with a 500 watt heating element was placed in the inner lock to duplicate the heat load and high humidity seen during manned chamber treatments. Two towels partially immersed in the water served as wicks.

All gas measurements were done using a fixed detector mass spectrometer (Perkin-Elmer Gas Analyzer or Chemetron Medspect 2). Measurements were recorded by an HP 1000 Computer at regular intervals.

Canister Flow

The canister flow estimates were done by the method of adding a known amount of CO_2 to the air in the chamber, then observing the rate of removal by the scrubber. The air flow through the scrubber canister is related to the rate of removal of CO_2 by the formula given in the results section. The studies were done with the inner lock compressed with air to simulated depths of 15, 30, 60 or 165 feet of seawater (FSW). Carbon dioxide was introduced into the chamber through 1/8" nylon tubing until the chamber CO_2 partial pressure reached approximately 0.016 atm. The heater-chiller blower was turned on to thoroughly mix the CO_2 with chamber air. Then the CO_2 scrubber blower was turned on and CO_2 samples continuously taken from approximately the center of the chamber at a position determined to give a representative sample of mixed chamber CO_2 concentration. The study ended when the chamber CO_2 partial pressure fell to approximately 0.002 atm.

The chamber CO_2 concentration was plotted as a function of time as discussed in the results section to give an estimate of the scrubber flow rate.

Canister Duration

The canister duration studies were done using the inner and outer locks which have a combined volume of 5,690 liters, at depths of 30, 60, and 165 FSW on air.

The chamber was first compressed to 4 FSW and CO_2 added to bring the initial chamber CO_2 concentration to the desired initial levels. Initial CO_2 levels were established at a calculated steady state value, and at values approximately 0.05 atm and 0.10 atm higher than steady state. These steady state estimates were calculated based on a CO_2 addition rate of 2 liters per minute and canister flow rates from the previous study. This calculation will be discussed later. Once the CO_2 level was established the chamber was compressed to the desired depth, and the heater-chiller blower turned on to mix the chamber.

At depth, CO_2 was added continuously to the chamber at approximately 2 standard liters per minute (SLPM) to simulate 3 occupants, 1 working (VO_2 = 1 ℓ/min) and 2 resting (VO_2 = 0.5 ℓ/min each). The CO_2 was added near the top of the inner chamber at a position estimated to provide good mixing. The CO_2 addition rate to the chamber was controlled by a needle valve which had been calibrated previously at all the above depths by flowing CO_2 into a weather balloon inside the chamber and measuring the contents of the balloon with a Tissot spirometer outside the chamber. Actual CO_2 injection rates in standard liters per minute (SLPM) were 2.04, 2.04, and 2.06 at depths of 30, 60 and 165 FSW respectively.

Having previously established the desired initial CO_2 level at 4 FSW, the scrubber blower was turned on and sampling begun as soon as the CO_2 flow of 2 SLPM was started. Mixed chamber samples were taken from three widely spaced locations for comparison to ensure that chamber contents were well mixed. A canister effluent sample was taken from the center of the canister discharge directly on top of the canister. Values were recorded at two minute intervals and plots of PCO_2 versus time were generated by an HP 1000 computer at the conclusion of each study.

RESULTS

Canister Flow Study

A typical canister flow study is shown in Figure 1 which is a plot of PCO_2 in %SEV (100% SEV = 1 atm) versus time. For a closed well mixed system in which no CO_2 is added after the initial PCO_2 is established, and in which canister effluent is constant, the chamber PCO_2 at any time t is given by the formula:

$$P_{CO_2} = P_{E_{CO_2}} - (P_{E_{CO_2}} - P_{S_{CO_2}})e^{-kt}$$

where:

$P_{E_{CO_2}}$ = Canister effluent CO_2 tension

$P_{S_{CO_2}}$ = Starting CO_2 tension

$k = \dot{V}_F/V_{CH}$

$\dot{V}_F$ = Scrubber ventilation rate (actual ℓ/min)

V_{CH} = Chamber floodable volume (liters)

t = Time in minutes

This equation can be rearranged to give:

$$(P_{CO_2} - P_{E_{CO_2}}) = (P_{S_{CO_2}} - P_{E_{CO_2}})e^{-kt}$$

and taking the natural log of each side:

$$LN(P_{CO_2} - P_{E_{CO_2}}) = (-kt) \cdot LN(P_{S_{CO_2}} - P_{E_{CO_2}})$$

In these experiments, the $P_{E_{CO_2}}$ was essentially zero so that the equation becomes:

$$LN(P_{CO_2}) = (-kt) \cdot LN(P_{S_{CO_2}})$$

When $LN(PCO_2)$ is plotted versus time, a straight line plot is obtained. Figure 2 shows a typical example. The slope of this plot (-k) is equal to the ratio of canister flow to chamber volume (V_F/V_{CH}). Since chamber volume is known (3,850 ℓ), the canister flow is easily calculated. Table 1 shows canister flows calculated in this manner at depths of 15, 30 and 60 FSW. Little change was noted with increasing depth. Flows at 165 FSW could not be measured using this technique because canister duration times were so short that canister effluent CO_2 tension began increasing before steady state was reached. The only manufacturer's specification available gives an air flow through the scrubber canister of 10 cubic feet per minute (280 liters per minute) at 1 atmosphere. This reasonably approximates our data at depths to 60 FSW.

Canister Duration Study

The data from all studies is summarized in Table 2, which gives the initial mixed chamber PCO_2 and the times required for canister effluent PCO_2 to reach 0.5% SEV and 1.0% SEV. Initial canister weights for each of the initial chamber PCO_2 levels are also noted.

Typical studies at 30, 60 and 165 FSW are shown in Figures 3, 4 and 5. After decreasing to a minimum, mixed chamber CO_2 levels increased again as canister effluent CO_2 increased. The average mixed chamber PCO_2 for each depth at the time canister effluent PCO_2 reached 0.5% SEV and 1.0% SEV is shown in Table 3. Note that as initial chamber PCO_2 increased, the rise in canister erfluent PCO_2 occurred sooner.

DISCUSSION

During a chamber treatment, the chamber initially is filled with fresh air at a CO_2 concentration of approximately 0.03%. Chamber occupants produce CO_2 at a rate which can be estimated, and a scrubber (or ventilation system) removes CO_2 at a rate depending on the rate of air flow through the scrubber (or ventilation exhaust). Since the air flow through a scrubber is fairly constant for a given depth, the CO_2 concentration will increase exponentially toward an asymptote. With an ideal canister in which the canister effluent remains zero, the asymptote can be calculated from the equation:

$$P_{CO_2} = (\dot{V}_{CO_2}/V_F)$$

where:

$\dot{V}_{CO_2}$ = production of CO_2 by occupants

$\dot{V}_F$ = scrubber ventilation rate

Note that this asymptote is independent of chamber volume.

The PCO_2 will remain at the asymptotic level until enough CO_2 absorbent is used up to cause the canister effluent to rise. In a real, non-ideal scrubber, the canister effluent PCO_2 is not zero, but tends to remain low

until a certain amount of absorbent is used up at which point it begins rising, as shown in Figures 3, 4 and 5. These figures also illustrate that as canister effluent PCO_2 rises, chamber PCO_2 also begins rising above asymptotic levels. If the canister is changed after the chamber PCO_2 has begun to rise, chamber PCO_2 will decrease toward the asymptotic level and remain at that level until canister effluent begins to increase again. The actual asymtotic CO_2 levels were determined from the PCO_2 vs time plots for each study as the minimum CO_2 levels. These asymptotic or steady state values are summarized in Table 4, which also includes the predicted steady state using the flow data, assuming an ideal canister effluent PCO_2 of zero.

The longest steady state period occurred at 30 FSW. At 60 and 165 FSW, the canister effluent begins rising more quickly, making prediction equations less useful. However, in all studies the chamber PCO_2 decreased toward a steady state level after an initially higher level.

Canister breakthrough is an arbitrary term given to a specific point during the gradual rise in canister effluent PCO_2 and canister duration is the time required to reach canister breakthrough. Since the ultimate purpose of the canister is to keep chamber PCO_2 below acceptable levels, the canister breakthrough should be an effluent PCO_2 which will still allow chamber PCO_2 to remain at or below 1.5% SEV, the recommended maximum for chambers stated in the U.S. Navy Diving Manual (1). Defining canister breakthrough as that point when canister effluent is 0.5% SEV meets this goal, although, in some cases at 165 FSW, there was experimental variation which resulted in chamber PCO_2 being above 1.5% SEV. The maximum time that a chamber is likely to be compressed to 165 FSW during a treatment is two hours, and mild elevations of PCO_2 beyond 1.5% SEV for such a short period does not appear to be harmful (2).

It appeared that while the steady state level of chamber PCO_2 was very consistent for each depth, the canister duration varied greatly with initial chamber PCO_2 load. If all the canister durations at 30 FSW from Table 2 are plotted versus initial chamber CO_2 load, a linear relationship is noted which has a high correlation coefficient ($R^2 = 0.99$) (Figure 6). This curve can be extended to predict a canister duration of 5.5 hours when the initial chamber PCO_2 is the same as room air, (0.03% by volume). Such an extrapolation and verification of the curve is supported by data from an unreported NEDU manned study, in which three chamber occupants took turns pedaling a bicycle ergometer to generate a total of approximately 2 ℓ/min CO_2 in the same chamber reported here. The canister duration at 30 FSW beginning with fresh air was 6.2 hours. If the canister is changed just as the canister effluent PCO_2 reaches 0.5% SEV, the chamber PCO_2 is 1.23% SEV, and this PCO_2 can be applied to the graph of Figure 6 to estimate subsequent canister duration, which is 3.46 hours. Similar plots can be done for the studies at 60 FSW and 165 FSW, giving canister durations of 1.89 hours and 1.16 hours respectively. These times would be considerably shorter than the initial duration when the chamber started out on fresh air.

Table 5 shows the predicted canister durations, rounded down to the nearest half hour. The table can serve as a guideline for chamber operators

in stocking HP Sodasorb, but should not be used in lieu of CO_2 monitoring equipment for determining when to change canisters because various factors will influence the actual canister durations. They are expected to be longer if there are fewer chamber occupants, if an oxygen built in breathing system with an overboard dump is used, or if the chamber is ventilated. Cold temperatures, inadequate packing of the canister, and increased CO_2 production from chamber occupants may shorten the duration. The best method of determining when to change canister contents operationally is by monitoring mixed chamber PCO_2, and absorbent should be changed when this value approaches 1.5% SEV. This is more desirable than using canister effluent values of 0.5% SEV because either low canister flow rates or increased chamber occupant CO_2 production could result in mixed chamber values well above 1.5% SEV while canister effluent values are still below 0.5% SEV. If canister changes are being made much more frequently than predicted by Table 5, however, monitoring canister effluent CO_2 will show whether the canister absorbent has been depleted or if the VCO_2/V_F ratio is too high. If the differences between canister effluent and mixed chamber PCO_2 are much greater than those shown in Table 3 then canister flow rate is too low for the amount of CO_2 being produced and corrective action must be taken. The first line of defense, obviously, is to increase blower speed if possible. If blower speed cannot be increased and CO_2 production cannot be decreased (e.g. tenders are working hard at resuscitation) then supplementary ventilation will be required.

Chamber CO_2 levels can be easily monitored with chemical detection tubes (e.g. Draeger CH 23501) which are rugged and reliable. It should be noted that when using a mixed chamber PCO_2 of 1.5% SEV to change canister contents, durations will be slightly longer than those shown in Table 5 if the conditions of VCO_2 and V_F are the same as in this study, or they may be shorter for the reasons noted above. Normally, canister changes would be made at a chamber PCO_2 of 1.5% SEV, but this study shows that even if changes are made at mixed chamber levels of 0.5 to 0.9% SEV greater, the chamber PCO_2 levels will rapidly return to asymtotic levels although the time to the next canister change will be shorter.

SUMMARY

A method of determining air flow through a DH-10 CO_2 scrubber at various depths in a recompression chamber is presented. These flows were used to predict the asymptotic levels CO_2 in the chamber which were used as the initial CO_2 levels in determining canister duration times. Canister durations based on a 0.5% SEV canister effluent PCO_2 of the DH-10 scrubber were found to be 3.46 hours at 30 FSW, 1.89 hours at 60 FSW, and 1.16 hours at 165 FSW. The canister duration time when the chamber starts out with fresh air, is likely to be longer. Operationally, mixed chamber PCO_2 levels, rather than canister effluent levels, should be monitored and canister contents changed when levels reach 1.5% SEV. Even if mixed chamber PCO_2 levels exceed 1.5% SEV by as much as 0.9% SEV when the absorbent is changed, the DH-10 will rapidly bring the PCO_2 down to asymptotic levels, although the canister duration will be shorter.

REFERENCES

1. U.S. Navy Diving Manual, Change 2, (Washington, D.C., U.S. Government Printing Office) 1978, Chapter 8.

2. Clark, J.M.; Tolerance and Adaptation to Acute and Chronic Hypercapnia in Man, In Proceedings, 1973 Diver's Gas Purity Symposium, Report No. 2-73, Battelle-Collumbus Laboratories, Columbus, Ohio, 1973.

TABLE 1

CANISTER FLOW

Depth (FSW)		Flow ℓ/min
15		296
		228
	Mean	262
30		274
60		278
		251
		260
		289
	Mean	270
	† S.D.	17

Manufacturer's Specification at 1 atmosphere is 280 ℓ/min.

TABLE 2

Canister Duration Times

FSW	Initial Mixed Chamber CO2(SEV)	Time to Reach Indicated Canister Effluent Tension: 0.5% CO_2 SEV	1.0% CO_2 SEV	H.P. Sodasorb in Canister
30	1.16%	3.6 hrs	4.4 hrs	8 lbs 5 oz
30	1.56	2.8	3.8	8 11
30	2.11	2.0	2.9	8 1
60	1.15	1.6	2.2	8 0
60	1.45	1.8	2.7	8 2
60	2.08	1.5	2.1	8 1
165	1.47	1.1	1.7	8 8
165	1.65	0.9	1.5	8 6
165	2.28	0.8	1.3	8 7
165	2.40	0.2	0.8	8 2

TABLE 3

Chamber CO_2 Tension at Canister Effluent Tensions of 1.0% SEV and 0.5% SEV

Depth in FSW	Number of Runs	Mixed Chamber CO_2 (% SEV) At Canister Effluent of 0.5% SEV	Mixed Chamber CO_2 in (% SEV) At Canister Effluent of 1.0% SEV
30	3	1.23 ± .08	1.63 ± .04
60	3	1.14 ± .08	1.53 ± .10
165	4	1.54 ± .26	1.75 ± .08

TABLE 4

Steady State Chamber CO_2
Average for Each Depth

FSW	Number of Runs	Observed $\pm$ S.D. (SEV)	Predicted From Flow Data (SEV)
30	3	.89 $\pm$ .06%	.82%
60	3	1.03 $\pm$ .12	.88
165	4	1.34 $\pm$ .17	1.25

TABLE 5

Predicted Intervals for Canister Change

Conditions:
(1) Standard 2-Lock Aluminum Recompression Chamber
(2) Three Occupants or Less
(3) Approximately 75°F (24°C) Internal Air Temperature
(4) DH-10 Scrubber Running at 24 Volts

DEPTH	TIME
30 FSW	3.5 Hours
60 FSW	1.5 Hours
165 FSW	1.0 Hours

FIGURE 1
SCRUBBER FLOW STUDY
DECREASE IN CHAMBER CO2 VERSUS TIME
60FSW

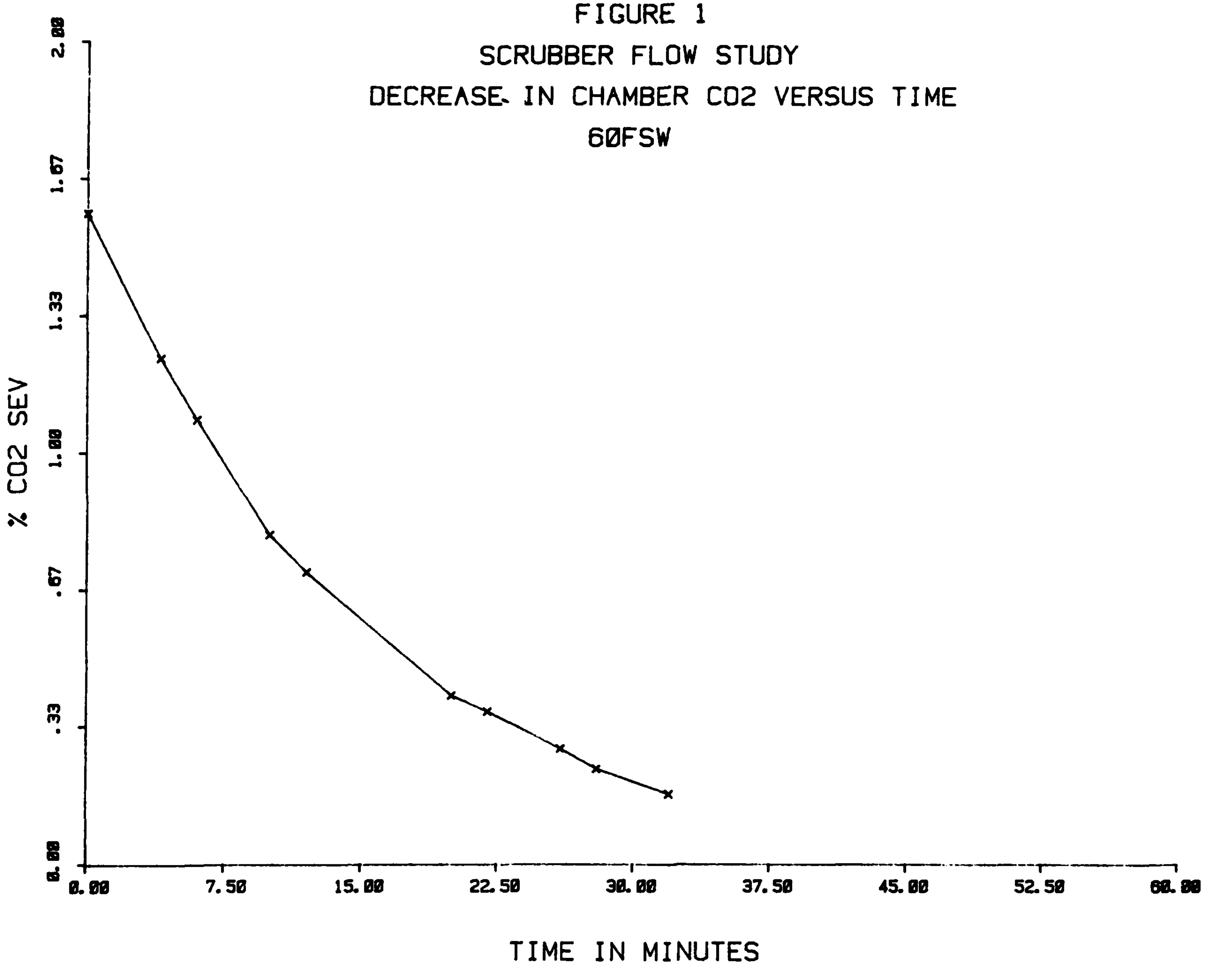


FIGURE 2
SCRUBBER FLOW STUDY
LOG N OF CHAMBER CO2 VERSUS TIME
60 FSW

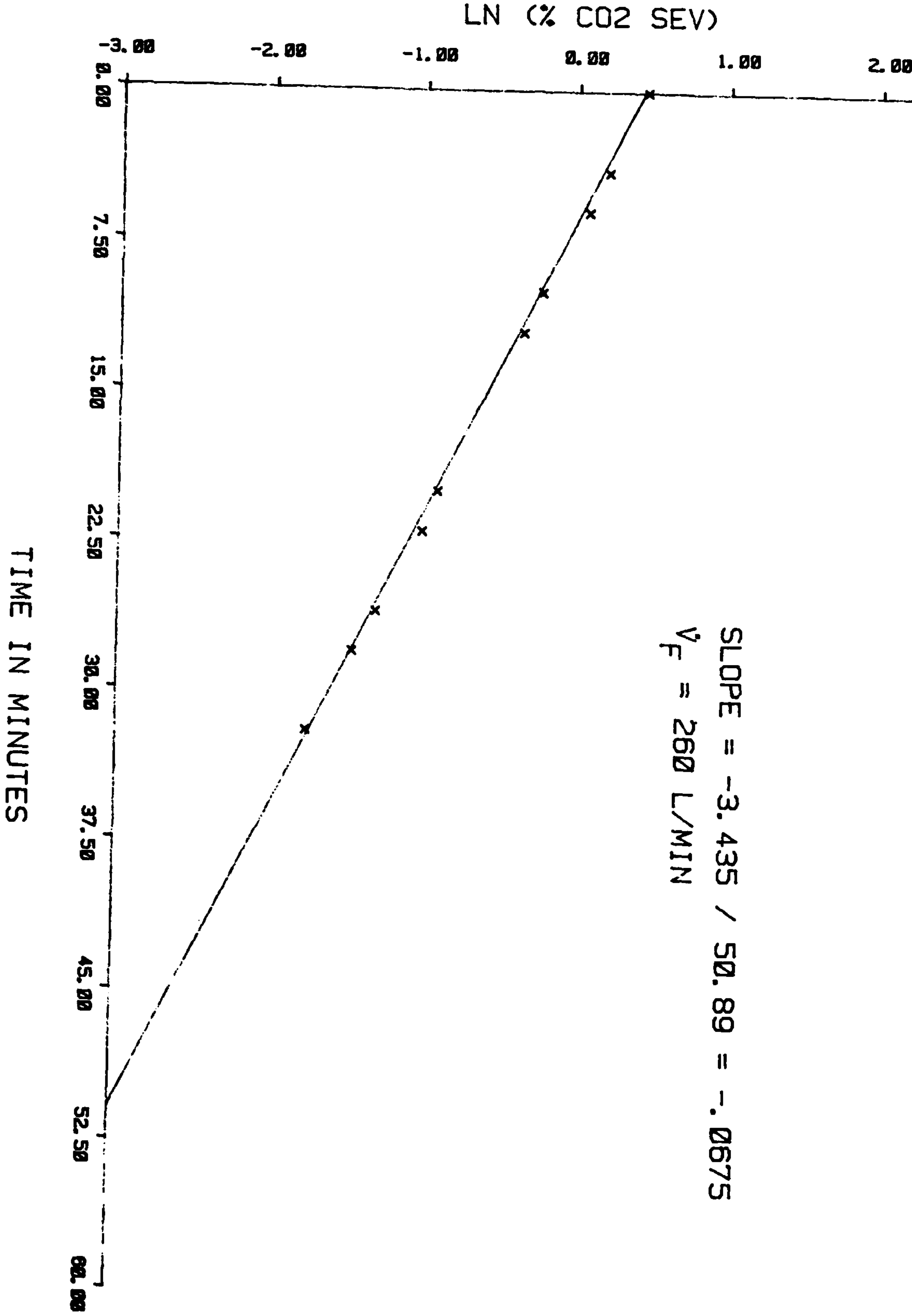


FIGURE 3

CANISTER DURATION STUDY

CO2 CONCENTRATION VERSUS TIME

30 FSW

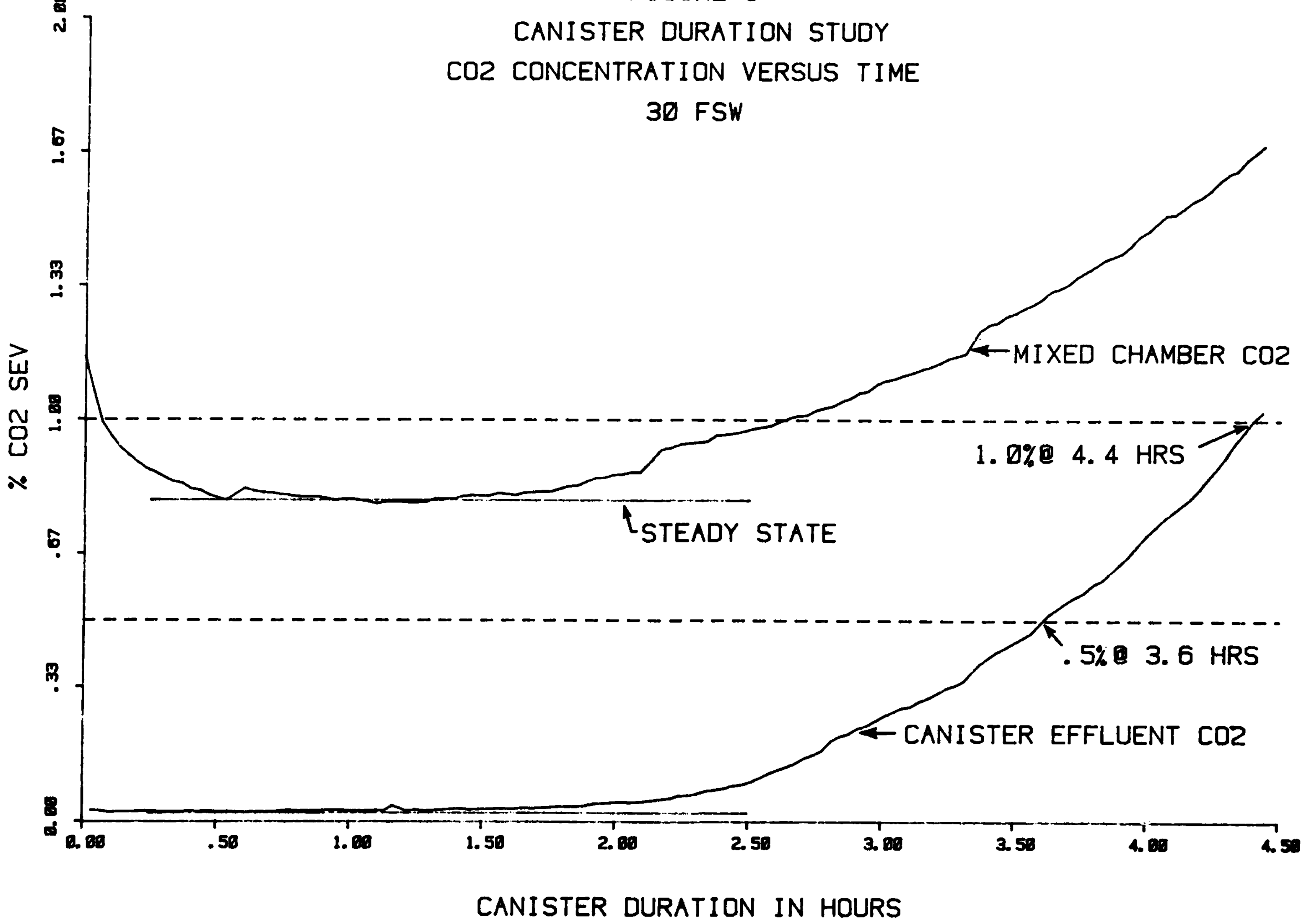


FIGURE 4

CANISTER DURATION STUDY

CO2 CONCENTRATION VERSUS TIME

60 FSW

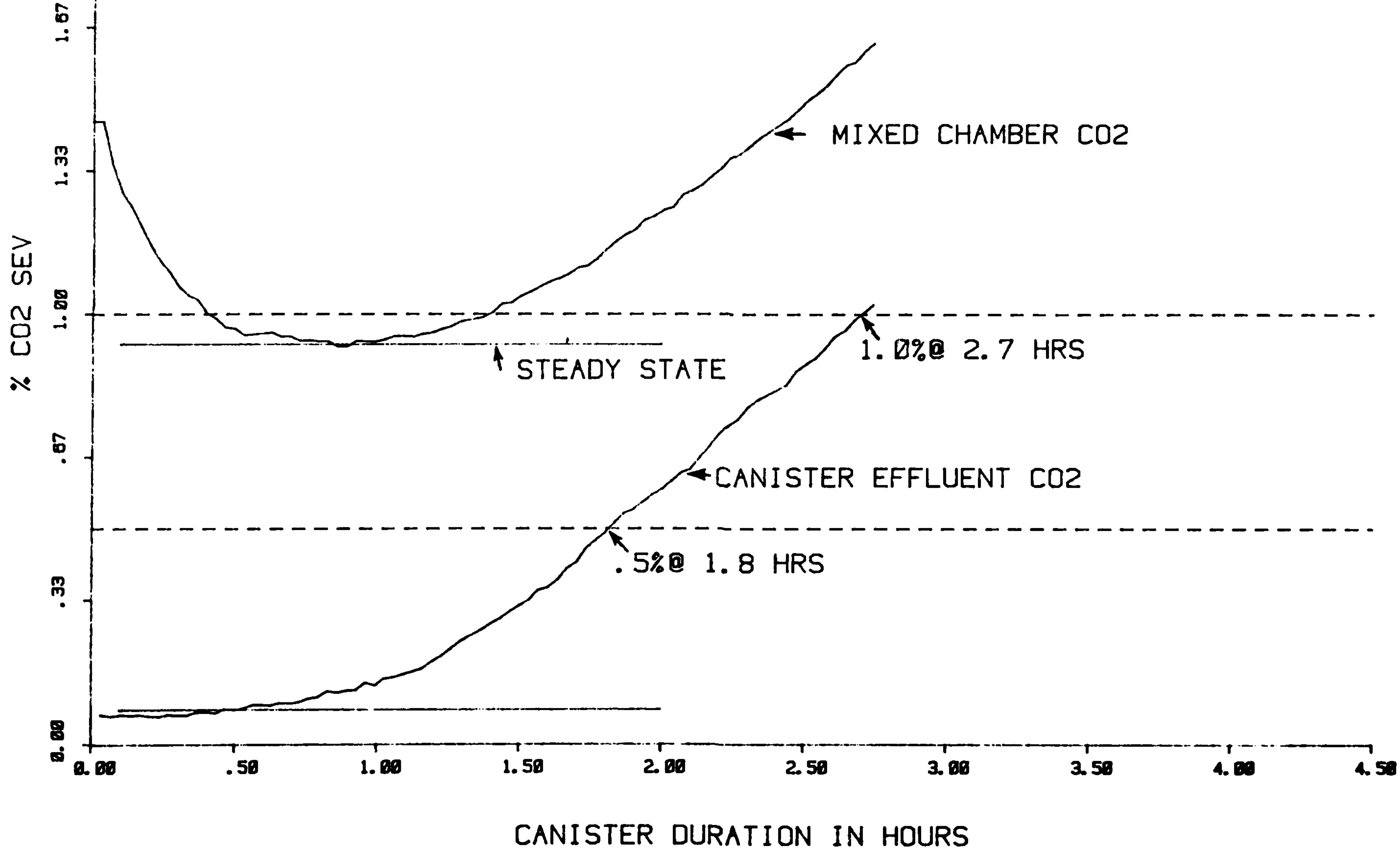


FIGURE 5
CANISTER DURATION STUDY
CO2 CONCENTRATION VERSUS TIME
165 FSW

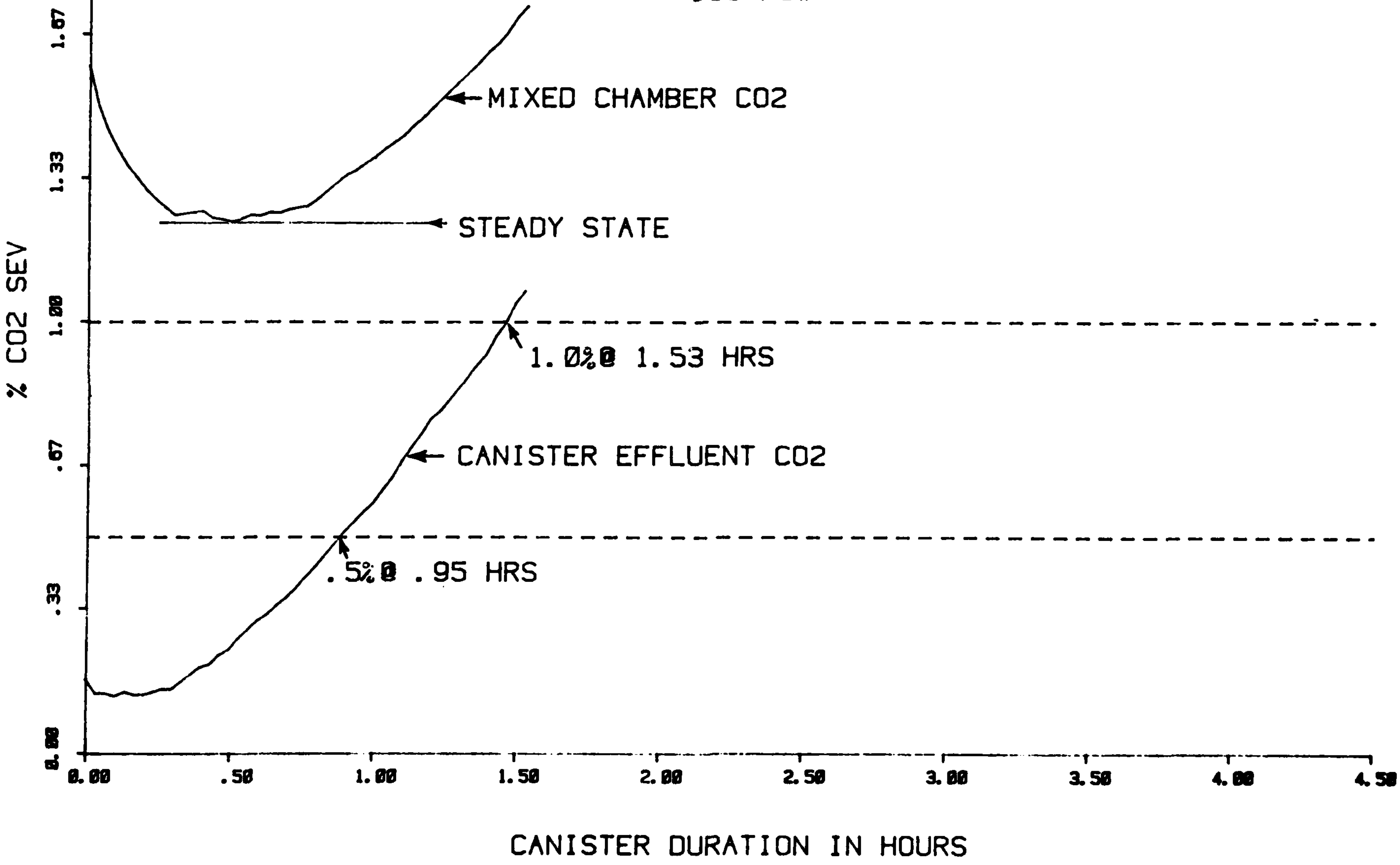
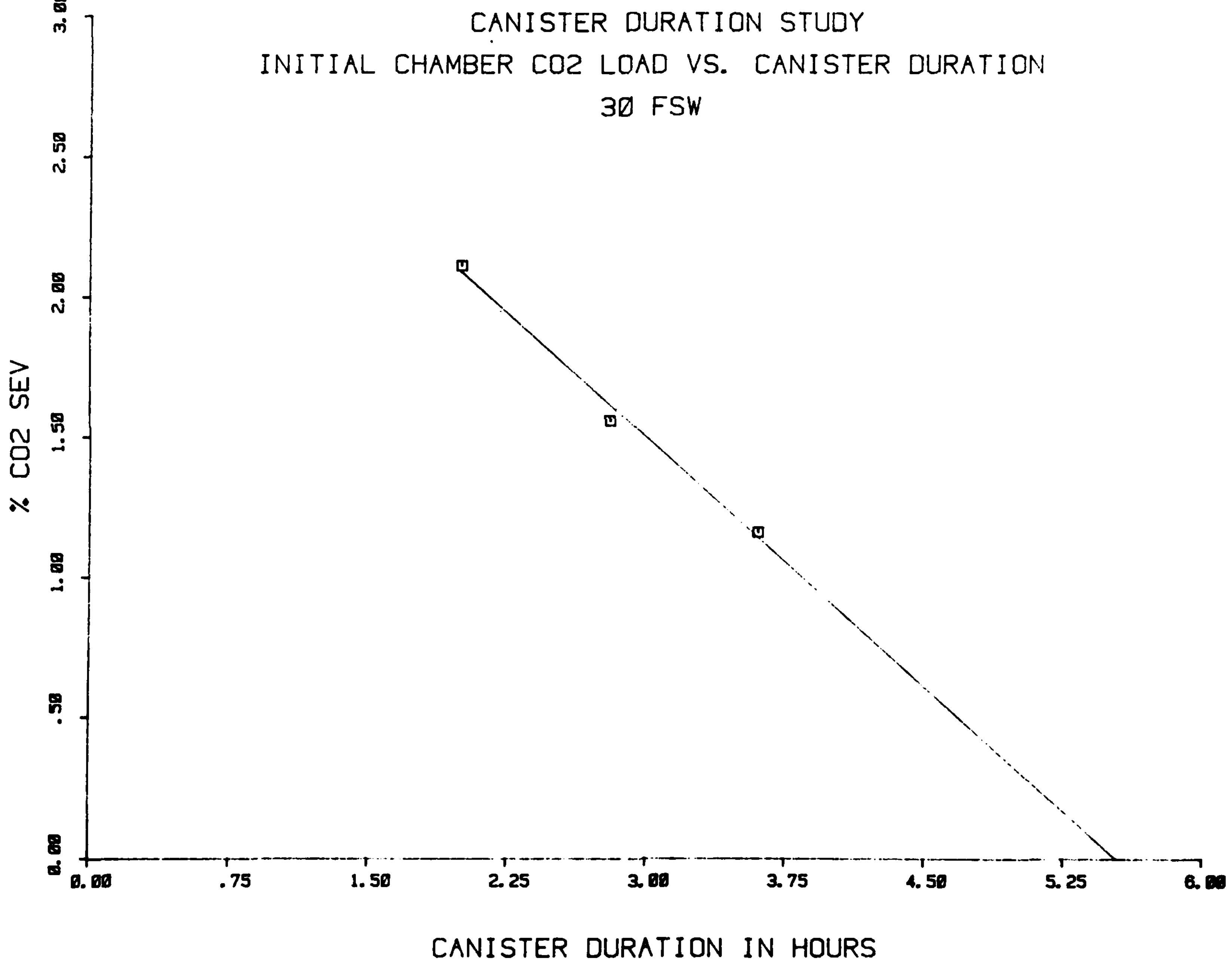


FIGURE 6
CANISTER DURATION STUDY
INITIAL CHAMBER CO2 LOAD VS. CANISTER DURATION
30 FSW



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